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The Influence of Flow and Temperature on Survival of Wild Subyearling Fall Chinook Salmon in the Snake River

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Abstract.—Summer flow augmentation to increase the survival of wild subyearling fall chinook salmon Oncorhynchus tshawytscha is implemented annually to mitigate for the development of the hydropower system in the Snake River basin, but the efficacy of this practice has been disputed. We studied some of the factors affecting survival of wild subyearling fall chinook salmon from capture, tagging, and release in the free-flowing Snake River to the tailrace of the first dam encountered by smolts en route to the sea. We then assessed the effects of summer flow augmentation on survival to the tailrace of this dam. We tagged and released 5,030 wild juvenile fall chinook salmon in the free-flowing Snake River from 1998 to 2000. We separated these tagged fish into four sequential within-year release groups termed cohorts ($N = 12$). Survival probability estimates to the tailrace of the dam for the 12 cohorts when summer flow augmentation was implemented ranged from 36±4% to 88±5%. We fit an ordinary least-squares multiple regression model from indices of flow and temperature that explained 92% ($N = 12$; $P \leq 0.0001$) of the observed variability in cohort survival. Survival generally increased with increasing flow and decreased with increasing temperature. We used the regression model to predict cohort survival for flow and temperature conditions observed when summer flow augmentation was implemented, and for the flow and temperature conditions had the summer flow augmentation not been implemented. Survival of all cohorts was predicted to be higher when flow was augmented, than when flow was not augmented, because summer flow augmentation increased the flow levels and decreased the temperatures fish were exposed to as they moved seaward. We conclude that summer flow augmentation increases the survival of young fall chinook salmon.

Survival of chinook salmon Oncorhynchus tshawytscha smolts during seaward migration is affected by biotic factors, some of which are controlled by the physical environment. Researchers have proposed that stream flow and temperature act together to influence survival of chinook salmon smolts (Kjelson et al. 1982; Kjelson and Brandes 1989; Connor et al. 1998). Dams have altered the flow and water temperature regimes of rivers in the western U.S., thereby contributing to declines in abundance of many stocks of chinook salmon by reducing smolt survival (e.g., Raymond 1988; Yoshiyama et al. 1998).

Raymond (1979) was the first to estimate survival for yearling Snake River spring and summer chinook salmon smolts, and to relate a decline in survival over years to dam construction. From 1966 to 1968, Raymond (1979) estimated that survival from the Salmon River to Ice Harbor Dam (Figure 1) for yearling spring and summer chinook salmon smolts was 85—95%. Between 1970 and 1975 Lower Monumental and Little Goose dams (Figure 1) were completed and smolt survival estimates to Ice Harbor Dam decreased to 10—50% (Raymond 1979). Raymond (1979) concluded that during high flow years lethal levels of dissolved gases killed yearling spring and summer chinook salmon smolts, whereas in low flow years mortality resulted from low reservoir water velocities, delayed reservoir passage, predation, and passage via dam powerhouses.

Wild subyearling chinook salmon that pass downstream in the lower Snake River reservoirs from May to August include spring, summer, and fall-run juveniles that are listed under the Endangered Species Act (NMFS 1992). Wild fall chinook salmon typically compose the majority of the subyearling smolts that pass downstream during summer in the lower Snake River (Connor et al. 2001a). The minority is composed of wild spring and summer chinook that disperse long distances from natal streams into the Snake River where they adopt an ocean-type life history similar to fall chinook salmon (Connor et al. 2001a, 2001b). For simplicity, we refer to all of the wild subyearling chinook salmon that inhabit the shorelines of the Snake River as fall chinook salmon.

Dam construction changed juvenile fall chinook salmon life history in the Snake River basin by eliminating production in the relatively warmer water of the historical spawning area, thereby restricting spawning to less productive cooler reaches of river (Connor et al. 2002). This helps explain why present-day smolts migrate seaward during summer in contrast to their pre-dam counterparts that migrated seaward in late spring (Connor et al. 2002). Summer flow augmentation is intended to help recover the Snake River stock of fall chinook salmon by mitigating dam-caused changes in life history timing (NMFS 1995).

Summer flow augmentation is made up of releases of water from Dworshak Reservoir and reservoirs upstream of Brownlee Dam (NMFS 1995; Connor et al. 1998; Figure 1). These releases increase flow and decrease water temperature in Lower Granite Reservoir (Connor et al. 1998; Figure 1). Summer flow augmentation increases the rate of seaward movement of fall chinook salmon passing downstream in Lower Granite Reservoir, and reduces the time smolts take to pass Lower Granite Dam (Figure 1) by an average of 1 to 5 d (Connor et al. in review).

Connor et al. (1998) concluded that summer flow augmentation also increased fall chinook salmon survival to Lower Granite Dam, and recommended that future studies should include sequential within-year releases of tagged fish and survival estimation using a mark-recapture approach. In this paper, we estimate survival from release in the free-flowing Snake River to the tailrace of Lower Granite Dam by using a mark-recapture approach. We test the effects of flow and water temperature on survival, and then assess the effect of summer flow augmentation on survival.

Methods

Data collection.—We analyzed data collected on fall chinook salmon from 1998 to 2000. Data for these years were selected because sample sizes of tagged fall chinook salmon were large, and tagged fish were not handled as they passed Lower Granite Dam. Field personnel captured fall chinook salmon by using a beach seine (Connor et al. 1998). Sampling typically started in April soon after fry began emerging from the gravel, and was conducted 3 d per week at permanent stations. Once a majority of fish were at least 60-mm fork length, additional stations were sampled 1-2 d/week for three consecutive weeks. Sampling was discontinued in June or July when the majority of fish had moved into Lower Granite Reservoir or points downstream.

Passive integrated transponder (PIT) tags (Prentice et al. 1990a) were inserted into parr 60-mm fork length and longer (Connor et al. 1998). Tagged parr were released at the collection site after a 15-min recovery period. Some of the PIT-tagged fish were detected as smolts as they passed downstream in the juvenile bypass system of Lower Granite Dam (Matthews et al. 1977), which is equipped with PIT-tag monitors (Prentice et al. 1990b).

After detection at Lower Granite Dam, the PIT-tagged smolts were routed through flumes back to the river. Smolts then had to pass seven more dams (Figure 1) to reach the Pacific Ocean. Little Goose, Lower Monumental, McNary, John Day, and Bonneville dams (Figure 1) were also equipped with monitoring systems that recorded the passage of PIT-tagged smolts that used the bypass systems, and then routed the bypassed fish back to the river.

Cohort survival.—The first step in the analysis was to divide the annual samples of PIT-tagged fall chinook salmon into four sequential within-year release groups referred to as cohorts. We divided the annual samples into cohorts based on estimated fry emergence dates. We estimated fry emergence date for each fish in two steps. First, the number of days since each PIT-tagged fish emerged from the gravel was calculated by subtracting 36 mm from its fork length measured at initial capture, and then dividing by the daily growth rate observed for recaptured PIT-tagged fish (range 0.9 to 1.3 mm/d; Connor and Burge in review). The 36-mm fork length for newly emergent fry was the mean of the observed minimum fork lengths. Second, emergence date was estimated for each fish by subtracting the estimated number of days since emergence from its date of initial capture, tagging, and release. We sorted the data in ascending order by estimated fry emergence date, and then divided it into four cohorts of approximately equal numbers of fish.

The single release-recapture model (Cormack 1964; Skalski et al. 1998) was used to estimate survival probability to the tailrace of Lower Granite Dam for each cohort. We insured that the single release-recapture model fit the data by using three assumption tests described by Burnham et al. (1987) and Skalski et al. (1998).

Variables.—Cohort survival was the dependent variable for the analysis. The predictor variables were: tagging date, median day of year fish from each cohort were captured, tagged, and released; fork length, mean fork length (mm) at capture, tagging, and release for the fish of each cohort; flow, a flow (m^3/s) exposure index calculated as the mean flow measured at Lower Granite Dam by U.S. Army Corps of Engineers personnel during the period when the majority of smolts from each cohort passed the dam; and temperature, a water temperature (°C) exposure index calculated as the mean temperature measured in the tailrace of Lower Granite Dam by U.S.

Army Corps of Engineers personnel during the period when the majority of smolts from each cohort passed the dam.

To determine when the majority of smolts passed Lower Granite Dam, the PIT-tag detection data were used to calculate a passage date distribution for each cohort including the 25th percentile, median, 75th percentile, range of non-outliers, and mild outliers (Figure 2). The date cutoffs for mild outliers were calculated as the 25th percentile minus the inter-quartile range multiplied by 1.5 (i.e., the lower fence; Ott 1993), and the 75th percentile plus the inter-quartile range multiplied by 1.5 (i.e., the upper fence; Ott 1993). The left whisker on the box plot in Figure 2 extends back to the earliest detection date (17 June) that was later than or equal to the lower fence, and the right whisker extends forward to the detection date (16 August) that was earlier than or equal to the upper fence. The asterisks in Figure 2 signify mild outliers that were earlier than the lower fence or later than the upper fence (Ott 1993). All but the mild outliers were considered to be in the majority. The mean flow exposure index calculated based on the passage date distribution in Figure 2 would be the average of the mean daily flows measured in the tailrace of Lower Granite Dam between 17 June and 16 August.

Model selection.—We calculated a Pearson correlation coefficient ($\underline{r}$) to test for collinearity among the predictor variables. Predictor variables that were correlated ($\underline{r} \geq 0.6$; $\underline{P} \leq 0.05$) were not entered into the same model.

We fit multiple regression models from every combination of non-collinear predictor variables. We compared fit among models based on Mallow's Cp scores (Dielman 1996), Akaike's information criteria (AIC; Akaike 1973), and the coefficient of determination ($\underline{R}^2$). The final (i.e., best) regression model had a Mallow's Cp score similar to the number of parameters, the lowest AIC value, the highest $\underline{R}^2$ value, and predictor variables with slope coefficients that differed significantly ($\underline{t} \geq 2.0$; $\underline{P} \leq 0.05$) from zero. Only the top three models are reported.

We made residual plots for each predictor variable in the final regression model as described for flow in the following example. Estimated survival was regressed against temperature. The residuals from this regression were then plotted against flow. A line was then fit to the residuals by regressing them against flow. The resulting residual plots provided a better graphical representation of the relation between survival and flow because the variability in survival attributable to temperature had been removed.

Assessing summer flow augmentation.—We assessed the effect of summer flow augmentation on cohort survival to the tailrace of Lower Granite Dam by comparing two predictions. First, we predicted cohort survival to the tailrace of Lower Granite Dam by entering the observed mean flow and water temperature exposure indices for each cohort into the final regression model. Cohort survival was then predicted a second time by entering mean flow and water temperature exposure indices into the final regression model that were recalculated to remove effects of summer flow augmentation.

The flow exposure index was recalculated after subtracting the daily volume of water released for summer flow augmentation (Appendix 1). The water temperature exposure index was recalculated using temperatures that were simulated for the tailrace of Lower Granite Dam under the flow conditions had the summer flow augmentation not been implemented (Appendix 2). Water temperatures were simulated using a one-dimensional heat budget model developed for the Snake River by the U.S. Environmental Protection Agency (Yearsley et al. 2001). Past model validation showed that daily mean water temperatures simulated for July and August were within an average of 1.1°C of those observed (Yearsley et al. 2001).

Results

During the 3 years, 5,030 fall chinook salmon were captured, PIT tagged, and released along the free-flowing Snake River. Annual sample sizes of PIT-tagged fall chinook salmon were 2,060 in 1998, 1,761 in 1999, and 1,209 in 2000. The number of fall chinook salmon in the resulting 12 cohorts was 302—515 (Table 1). Emergence dates, tagging dates, fork lengths, and water temperature exposure indices generally increased from cohort 1 to 4 (Table 1). Flow exposure indices and survival estimates decreased from cohort 1 to 4 (Table 1).

Survival Modeling

Tagging date and fork length were negatively correlated ($N = 12$; $r = -0.76$; $P = 0.004$). Therefore, tagging date and fork length were not entered into the same multiple regression model. Fork length and flow ($N = 12$; $r = 0.47$; $P = 0.12$), fork length and temperature ($N = 12$; $r = -0.54$; $P = 0.07$), and flow and temperature ($N = 12$; $r = -0.45$; $P = 0.15$) were non-collinear.

The model that predicted cohort survival from flow and temperature had a Mallow's Cp score one less than the number of parameters, the lowest AIC value, and an R^2 of 0.92 (Table 2). The models that included fork length or tagging date had Mallow's Cp scores that equaled the number of parameters, relatively low AIC values, and R^2 values of 0.92 (Table 2), but the slope coefficient for fork length ($t = 0.05$; $P = 0.96$) and tagging date ($t = 0.07$; $P = 0.94$) did not significantly differ from zero.

The final multiple regression model was: Cohort survival = 140.82753 + 0.02648 Flow - 7.14437 Temperature. The final model was significant ($N = 12$; $P \leq 0.0001$) as were the coefficients for flow ($t = 6.81$; $P \leq 0.0001$) and temperature ($t = -3.96$; $P = 0.003$). Flow and temperature explained 92% of the observed variability in cohort survival to the tailrace of Lower Granite Dam. Cohort survival generally increased as flow increased, and decreased as temperature increased (Figure 3).

Assessing Summer Flow Augmentation

Water releases for summer flow augmentation in 1998, 1999, and 2000 were generally timed to coincide with the passage of later migrating smolts at Lower Granite Dam (Figures 4—6). Therefore, later cohorts were usually predicted to accrue greater survival benefits than earlier cohorts (Table 3). For all cohorts, estimated survival to the tailrace of Lower Granite Dam was predicted to be higher when summer flow augmentation was implemented than when it was not implemented (Table 3; Figure 7).

Discussion

Survival of wild subyearling fall chinook salmon from release in the Snake River to the tailrace of Lower Granite Dam generally increased as flow increased and decreased as temperature increased. Based on the regression model we developed, survival is predicted to change by approximately 3% with each change of 100 m^3/s in flow when temperature is held constant. The change in survival is approximately 7% for each 1°C increase or decrease in temperature when flow is held constant. Kjelson et al. (1982), Kjelson and Brandes (1989), and Connor et al. (1998) also reported that survival of subyearling chinook salmon during seaward migration is directly proportional to flow and inversely proportional to temperature.

Flow and temperature were closely correlated in the above three studies (e.g., $r = -0.999$; Connor et al. 1998), thus the researchers could not determine if the high correlation between survival and one variable was caused by the other variable. Flows and temperatures were atypically uncorrelated ($\underline{r} = -0.45$) from 1998 to 2000, therefore we were able to enter both of these predictor variables in the same multiple regression equation without detectably biasing the regression coefficients. Both regression coefficients differed significantly from zero (flow $\underline{P} \leq 0.0001$; temperature $\underline{P} = 0.003$). We conclude that flow and temperature act together to influence fall chinook salmon survival.

Correlation does not imply causation unless the causal mechanisms can be identified with certainty. Flow and water temperature, however, are the two most plausible factors affecting survival since fall chinook salmon are aquatic poikilotherms. We suggest that the two variables simultaneously assert their influence on survival. For example, flow influences rate of seaward movement (Berggren and Filardo 1993; Connor et al. in review) and water turbidity at the same time temperature is regulating predation (Vigg and Burley 1991; Curet 1994; Anglea 1997). Fall chinook salmon that migrate downstream when flow is low and temperatures are warm might suffer high mortality because they are exposed for longer durations to actively feeding predators in clear water.

Slow downstream movement and late-summer passage associated with low flow levels (Connor et al. in review) can also result in exposure to temperatures above 20°C. Prolonged exposure to temperatures above 20°C might disrupt fall chinook salmon growth, smoltification, and downstream movement, thereby exacerbating predation (Marine 1997). Temperatures above 20°C have also been associated with disease and stress-induced mortality (W. P. Connor, unpublished data).

Management Implications

Discussing the management implications of the results in this paper requires an understanding of the limitations on our study. Post-tagging mortality of cohorts released later in the summer would bias our analyses. Though Prentice et al. (1990a) found that delayed mortality of subyearling fall chinook salmon was low (range, 1—5%) 135—139 d after PIT tagging, their tests were not conducted at temperatures above 14.4°C. Research should be conducted on delayed mortality of PIT-tagged fall chinook salmon at temperatures above 14.4°C. We could not ascertain where PIT-tagged fall chinook salmon died en route to Lower Granite Dam. Our assessment of summer flow augmentation would be weakened if the majority of tagged fish died in the free-flowing Snake River before flow was augmented. On the other hand, the effect of summer flow augmentation on survival may have been underestimated because observed passage dates were used when recalculating flow and water temperature exposure indices. Estimates suggest that smolts passed Lower Granite Dam earlier when summer flow augmentation was implemented, than when it was not implemented (Connor et al. in review). Therefore, the recalculated flow exposure indices used in this paper were probably too high, the water temperature exposure indices were too low, and survival predictions made using these indices were probably higher than would be the case if flows had not been augmented.

In spite of these limitations, we believe the results in this paper support summer flow augmentation as a beneficial interim recovery measure for Snake River fall chinook salmon. Survival for all cohorts was predicted to be higher when flow augmentation was implemented than when flow was not augmented. We conclude that increases in flow and decreases in water temperature resulting from summer flow augmentation increase survival of young fall chinook salmon.

Although summer flow augmentation likely increased survival of fall chinook salmon passing downstream in Lower Granite Reservoir, mortality is likely still higher than before dams were constructed. When the lower Snake River was still free-flowing, the latest emigrating juvenile chinook salmon were exposed to mean June flows of approximately 2,800 m^3/s in 1954 and 3,800 m^3/s in 1955 (estimated from Figure 8 in Mains and Smith 1964). Mean June temperatures for 1954 and 1955 were approximateyly 9 and 10°C, respectively (estimated from Figure 8 in Mains and Smith 1964). In contrast, the latest emigrating cohorts of fall chinook salmon during 1998—2000 were exposed to mean flows of 859—1,299 m^3/s and mean temperatures of 18.3—19.8°C.

Releasing larger volumes of cooler reservoir water during the summer would provide present-day fall chinook salmon with velocity and temperature conditions more similar to their pre-dam counterparts. Dworshak Reservoir and reservoirs upstream of Brownlee Dam, however, are the only two sources of additional water. The ability of fishery managers to obtain more cool water for summer flow augmentation from Dworshak Reservoir is limited by supply and competing demands. Dworshak Reservoir is routinely drafted to near minimum operation levels, so releasing more water would reduce the probability of refill the next year. Releasing larger volumes of water from Dworshak Reservoir earlier in the year to cover a larger percentage of the smolt migration would be difficult because of conflicts with summer recreation.

Releasing the coldest water available from Dworshak Reservoir using the multi-level selector gates of Dworshak Dam would likely disrupt growth and seaward movement of fall chinook salmon that are still rearing in the lower Clearwater River when smolts from the Snake River are passing downstream in Lower Granite Reservoir (Connor et al. 2002). For example, the release of 6°C water in July 1994 decreased temperature in Lower Granite Reservoir from approximately

23 to 17°C (Connor et al. 1998), thereby improving conditions for survival of smolts from the Snake River. However, the 6°C release also caused water temperature in the lower Clearwater River to decrease from approximately 19 to 8°C (U. S. Geological Survey data collected at Spalding, Idaho) at a time when young fall chinook salmon were still rearing along the shoreline.

Increasing the supply of water available from reservoirs upstream of Brownlee Dam for summer flow augmentation would be difficult because of supply and competing demands. Cooler water cannot be released from Brownlee Reservoir because Brownlee Dam does not have multi-level selector gates. Consequently, the water released from Brownlee Reservoir for summer flow augmentation is relatively warm (e.g., 17.5 to 20.3°C; Connor et al. 1998). Developing the ability to selectively release cooler water from Brownlee Reservoir might be the most practical option for improving the effectiveness of summer flow augmentation provided that cool oxygenated water is available and impacts on native resident fishes would be minimal. Cool water could be released from Brownlee Reservoir when fall chinook salmon smolts from the Snake River are passing downstream in Lower Granite Reservoir without affecting water temperatures in the lower Clearwater River when fry and parr are still rearing.

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Appendix 1.—Mean daily flows (m^3/s) in Lower Granite Reservoir with and without summer flow augmentation, 1998 to 2000.

Date	1998		1999		2000	
	With	Without	With	Without	With	Without
01-Jul	2195	2138	2336	2243	1020	892
02-Jul	2212	2127	2212	2050	952	790
03-Jul	2251	2130	1931	1863	1014	835
04-Jul	2419	2283	1832	1702	977	816
05-Jul	2274	2116	1699	1594	1020	677
06-Jul	2065	1957	1685	1546	1090	773
07-Jul	1960	1844	1563	1427	1121	793
08-Jul	1827	1592	1546	1385	1059	552
09-Jul	1801	1515	1648	1458	1246	753
10-Jul	1778	1436	1563	1357	1198	583
11-Jul	1866	1385	1509	1269	1204	612
12-Jul	1892	1504	1532	1294	1274	572
13-Jul	1745	1087	1447	1136	1280	600
14-Jul	1812	1198	1529	1184	1229	513
15-Jul	1759	1164	1507	1172	1184	561
16-Jul	1651	1073	1507	1212	1161	501
17-Jul	1583	971	1475	1136	1187	507
18-Jul	1555	830	1541	1238	1087	524
19-Jul	1549	844	1501	991	1073	470
20-Jul	1577	881	1546	988	1099	504
21-Jul	1521	739	1456	954	1096	490
22-Jul	1535	719	1453	912	1028	450
23-Jul	1549	714	1456	895	1028	541
24-Jul	1512	688	1376	847	1005	382
25-Jul	1481	685	1354	824	1051	399
26-Jul	1444	646	1345	787	1076	467
27-Jul	1521	657	1314	762	1042	416
28-Jul	1529	762	1308	824	1031	515
29-Jul	1410	615	1257	685	860	436
30-Jul	1453	666	1263	671	643	530

Appendix 1.—(Continued)

31-Jul	1439	649	1368	634	855	453
01-Aug	1450	830	1357	617	833	408
02-Aug	954	765	1382	632	864	428
03-Aug	963	612	1323	615	784	402
04-Aug	1283	705	1303	702	748	337
05-Aug	1167	586	1266	660	833	413
06-Aug	1201	634	1175	615	776	360
07-Aug	1065	592	1181	640	759	351
08-Aug	1107	671	1198	753	745	354
09-Aug	943	436	1116	555	733	326
10-Aug	1065	510	1141	671	813	362
11-Aug	1045	484	1054	600	813	377
12-Aug	1104	524	1028	547	733	280
13-Aug	1136	552	1164	694	787	368
14-Aug	1087	496	1028	697	773	362
15-Aug	1028	496	1090	702	750	297
16-Aug	960	524	1073	657	753	261
17-Aug	827	396	1170	711	799	365
18-Aug	954	445	1022	595	767	252
19-Aug	974	413	1025	578	858	408
20-Aug	1065	566	1070	544	787	354
21-Aug	932	521	1051	637	787	391
22-Aug	787	487	906	538	649	329
23-Aug	716	498	898	462	677	365
24-Aug	719	490	997	569	691	354
25-Aug	688	487	892	487	671	331
26-Aug	683	552	960	569	685	428
27-Aug	575	462	901	467	583	360
28-Aug	617	402	912	583	677	354
29-Aug	697	544	827	527	566	362
30-Aug	592	541	810	552	513	346
31-Aug	507	334	782	476	518	368

Appendix 2.—Mean water temperatures (°C) in Lower Granite Reservoir with and without summer flow augmentation, 1998 to 2000.

	1998		1999		2000	
Date	With	Without	With	Without	With	Without
01-Jul	16.6	19.0	15.8	16.2	18.8	17.8
02-Jul	17.5	19.8	15.9	16.6	19.1	18.2
03-Jul	18.1	20.1	16.0	16.9	19.4	18.7
04-Jul	18.7	20.1	15.8	16.8	19.4	18.9
05-Jul	19.0	20.3	15.8	17.0	19.0	19.2
06-Jul	19.0	20.1	15.7	17.0	18.7	19.3
07-Jul	19.3	19.7	15.7	16.8	18.4	20.0
08-Jul	19.7	19.7	16.0	17.0	18.0	20.1
09-Jul	20.1	19.5	16.8	16.7	17.9	20.3
10-Jul	20.6	19.7	17.3	17.1	18.1	19.7
11-Jul	20.7	19.5	17.7	17.3	18.3	19.2
12-Jul	20.8	20.0	18.2	18.1	18.0	19.3
13-Jul	20.5	20.4	18.6	18.5	18.0	19.3
14-Jul	20.2	20.6	18.9	18.7	18.2	19.1
15-Jul	20.0	20.7	19.3	19.0	18.6	19.0
16-Jul	19.7	20.7	19.7	19.3	18.9	18.8
17-Jul	19.9	20.7	19.6	19.8	19.1	19.3
18-Jul	19.9	20.8	19.8	20.1	19.0	19.6
19-Jul	20.4	20.9	19.6	20.3	19.0	19.7
20-Jul	20.4	21.3	19.2	20.2	18.9	19.9
21-Jul	20.9	21.8	19.1	19.9	19.1	20.3
22-Jul	20.7	22.0	19.1	19.9	19.2	20.3
23-Jul	20.1	22.2	18.9	19.7	19.4	20.2
24-Jul	19.7	22.4	18.7	19.8	19.6	20.6
25-Jul	19.5	22.6	18.9	19.5	19.7	20.8
26-Jul	19.7	22.7	19.1	19.3	19.5	21.0
27-Jul	19.7	23.0	19.2	19.4	19.4	21.2
28-Jul	19.7	22.9	18.9	19.9	19.5	21.2
29-Jul	20.2	23.1	19.0	21.0	19.5	21.6
30-Jul	20.1	23.3	19.3	21.2	19.4	21.7

Appendix 2.—(Continued)

31-Jul	20.2	23.7	19.8	20.8	19.4	21.8
01-Aug	20.0	23.8	20.1	21.0	19.3	22.0
02-Aug	19.9	23.9	20.0	21.2	19.2	21.9
03-Aug	20.0	24.0	19.5	21.2	19.2	22.0
04-Aug	20.2	24.3	18.1	21.3	18.9	22.3
05-Aug	21.0	24.4	18.9	21.2	19.0	22.6
06-Aug	20.9	24.1	18.8	21.8	19.1	22.4
07-Aug	20.7	23.9	18.6	22.4	19.0	22.6
08-Aug	21.0	23.5	18.5	22.6	19.0	22.8
09-Aug	21.2	23.5	18.5	22.6	19.0	22.5
10-Aug	20.8	23.4	18.2	23.2	19.0	22.5
11-Aug	20.1	23.2	18.1	22.8	18.8	22.6
12-Aug	19.9	23.3	18.1	22.9	19.0	22.4
13-Aug	20.0	23.3	18.0	22.8	18.9	22.6
14-Aug	20.2	23.4	18.1	22.8	18.8	23.0
15-Aug	20.0	23.6	18.0	22.7	18.6	23.1
16-Aug	19.9	23.4	17.8	22.3	18.4	23.2
17-Aug	20.0	23.1	17.9	22.2	18.3	23.4
18-Aug	19.9	22.6	17.8	22.1	17.8	23.3
19-Aug	19.8	22.3	18.1	21.9	17.7	23.2
20-Aug	19.3	22.2	18.1	21.9	17.6	23.0
21-Aug	18.9	22.4	18.4	21.9	17.7	23.0
22-Aug	18.7	22.4	18.6	22.1	17.8	23.0
23-Aug	18.5	22.5	19.2	21.5	17.7	22.6
24-Aug	18.6	22.3	19.4	21.1	17.5	22.9
25-Aug	18.6	22.0	19.3	20.9	17.4	22.7
26-Aug	18.8	22.2	19.3	20.9	17.1	22.5
27-Aug	18.9	21.8	19.3	20.6	17.0	22.2
28-Aug	19.5	21.9	19.5	20.6	17.4	22.0
29-Aug	19.9	21.5	19.4	21.4	17.7	22.0
30-Aug	20.0	21.7	19.0	21.9	17.7	21.7
31-Aug	20.4	21.5	19.2	21.9	17.6	21.5

Table 1.—Emergence dates, predictor variables, and estimates of survival probability (%±SE) to the tailrace of Lower Granite Dam for each cohort of wild subyearling fall chinook salmon, 1998 to 2000. Predictor variables: Tagging date, median day of year of tagging; Fl, mean fork length (mm) at tagging; Flow, a flow (m^3/s) exposure index calculated as the mean flow measured at Lower Granite Dam during the period when the majority of smolts passed the dam; and Temperature, a water temperature (°C) exposure index calculated as the mean temperature measured in the tailrace of Lower Granite Dam during the period when the majority of smolts passed the dam.

Cohort	N	Emergence date	Tagging date	Fl	Flow	Temperature	Survival
			1998				
1	515	7 April	140	80	2,344	17.6	70.8±2.9
2	515	15 April	141	75	2,021	18.7	66.1±3.3
3	515	23 April	153	73	1,898	19.0	52.8±3.1
4	515	7 May	167	70	1,299	19.8	35.6±2.9
			1999				
1	441	20 April	147	80	2,378	16.3	87.7±4.6
2	440	30 April	153[A]	77	1,963	17.1	77.0±3.8
3	440	5 May	152[A]	70	2,116	16.7	81.2±5.8
4	440	13 May	167	68	1,353	18.3	36.4±3.5
			2000				
1	303	6 April	130	77	1,510	16.7	57.1±4.1
2	302	15 April	144	77	1,296	17.6	53.4±4.2
3	302	22 April	146	77	1,274	17.8	44.4±3.6
4	302	29 April	158	71	859	18.5	35.7±4.3

[A] Fish from cohort 2 emerged earlier than fish of cohort 3, but they were initially captured, tagged, and released later than fish of cohort 3.

Table 2.—Mallow's Cp scores, Akaikes information criteria (AIC), and coefficients of determination ($\underline{R}^2$) used to compare the fit of multiple regression models describing the survival of cohorts of wild subyearling fall chinook salmon from tagging in the Snake River to the tailrace of Lower Granite Dam, 1998 to 2000. Predictor variables: Tagging date, median day of year of tagging; Fl, mean fork length (mm) at tagging; Flow, a flow (m^3/s) exposure index calculated as the mean flow measured at Lower Granite Dam during the period when the majority of smolts passed the dam; and Temperature = a water temperature (°C) exposure index calculated as the mean temperature measured in the tailrace of Lower Granite Dam during the period when the majority of smolts passed the dam.

C(p)	AIC	$\underline{R}^2$	Variables in model
2	44	0.92	Flow, Temperature
4	46	0.92	Fl, Flow, Temperature
4	46	0.92	Tagging date, Flow, Temperature

Table 3.—Predicted survival (%±95% C.I.) to the tailrace of Lower Granite Dam for cohorts of wild subyearling fall chinook salmon tagged in the Snake River from 1995 to 1998. Predictions were made using the observed flow and water temperature indices in Table 1 (Survival with), and by using flow (m^3/s) and water temperature (°C) exposure indices recalculated to approximate conditions that would have occurred if flow had not been augmented (Survival without).

Cohort	Survival with	Recalculated		Survival without	Difference in survival
		Flow	Temperature		
			1998		
1	77.2±6.5	2,066	18.3	64.8±5.8	12.4
2	60.7±6.6	1,689	19.3	47.7±7.0	13.0
3	55.3±6.8	1,468	20.1	36.1±9.3	19.2
4	33.8±8.0	988	21.3	14.8±13.1	19.0
			1999		
1	87.3±7.5	2,128	17.1	75.0±5.2	12.3
2	70.6±4.7	1,667	18.4	53.5±4.3	17.1
3	77.5±5.8	1,837	18.0	60.9±4.0	16.6
4	45.9±4.6	943	20.1	22.2±9.4	23.7
			2000		
1	61.5±6.7	1,314	17.0	54.2±6.8	7.3
2	49.4±5.5	1,078	17.9	41.5±6.5	7.9
3	47.4±5.3	978	18.6	33.8±6.7	13.6
4	31.4±7.5	587	20.1	12.8±10.6	18.6

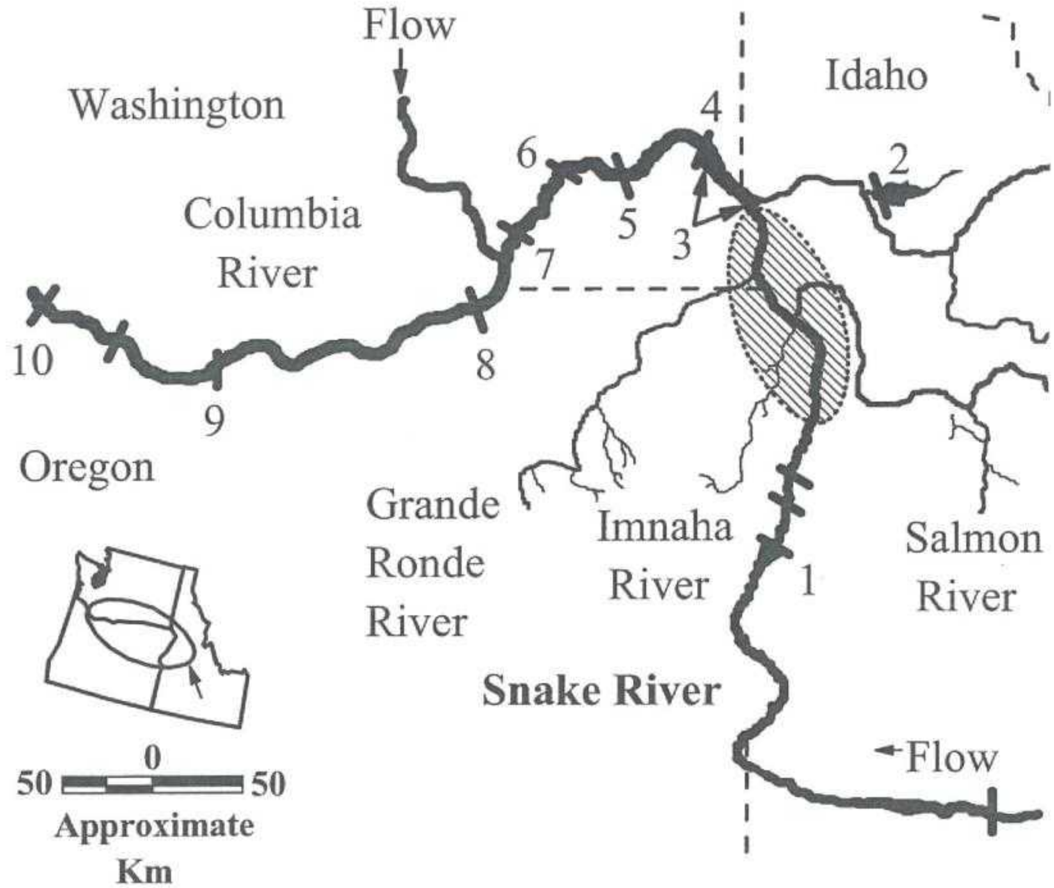


Figure 1.—Locations of the free-flowing Snake River where adult fall chinook salmon spawn and their offspring were captured by using a beach seine (cross hatched ellipse; rkm 224 to rkm 361) and other landmarks mentioned in the text. The locations are as follows: 1 = Brownlee Dam; 2 = Dworshak Reservoir; 3 = Lower Granite Reservoir; 4 = Lower Granite Dam (PIT-tag monitoring); 5 = Little Goose Dam (PIT-tag monitoring); 6 = Lower Monumental Dam (PIT-tag monitoring); 7 = Ice Harbor Dam; 8 = McNary Dam (PIT-tag monitoring); 9 = John Day Dam (PIT-tag monitoring), and 10 = Bonneville Dam (PIT-tag monitoring).

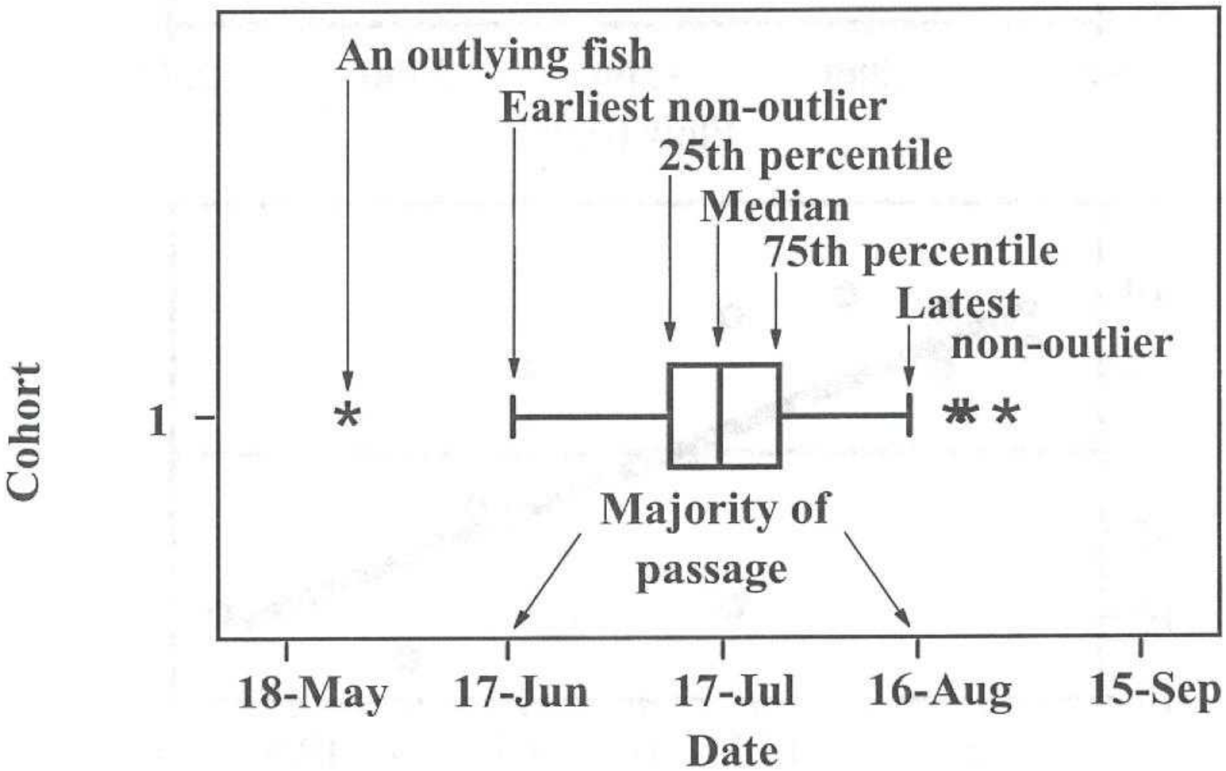


Figure 2.—An example of a passage date distribution for PIT-tagged wild subyearling fall chinook salmon at Lower Granite Dam including the time period that was used to represent the majority of passage for calculating flow and water temperature exposure indices. The left whisker on the box plot extends back to the earliest detection date (17 June) that was later than or equal to the lower fence (25th percentile minus the interquartile range multiplied by 1.5), and the right whisker extends forward to the detection date (16 August) that was earlier than or equal to the upper fence (75th percentile plus the interquartile range multiplied by 1.5). The asterisks signify mild outliers (one asterisk represents one fish) that were earlier than the lower fence or later than the upper fence.

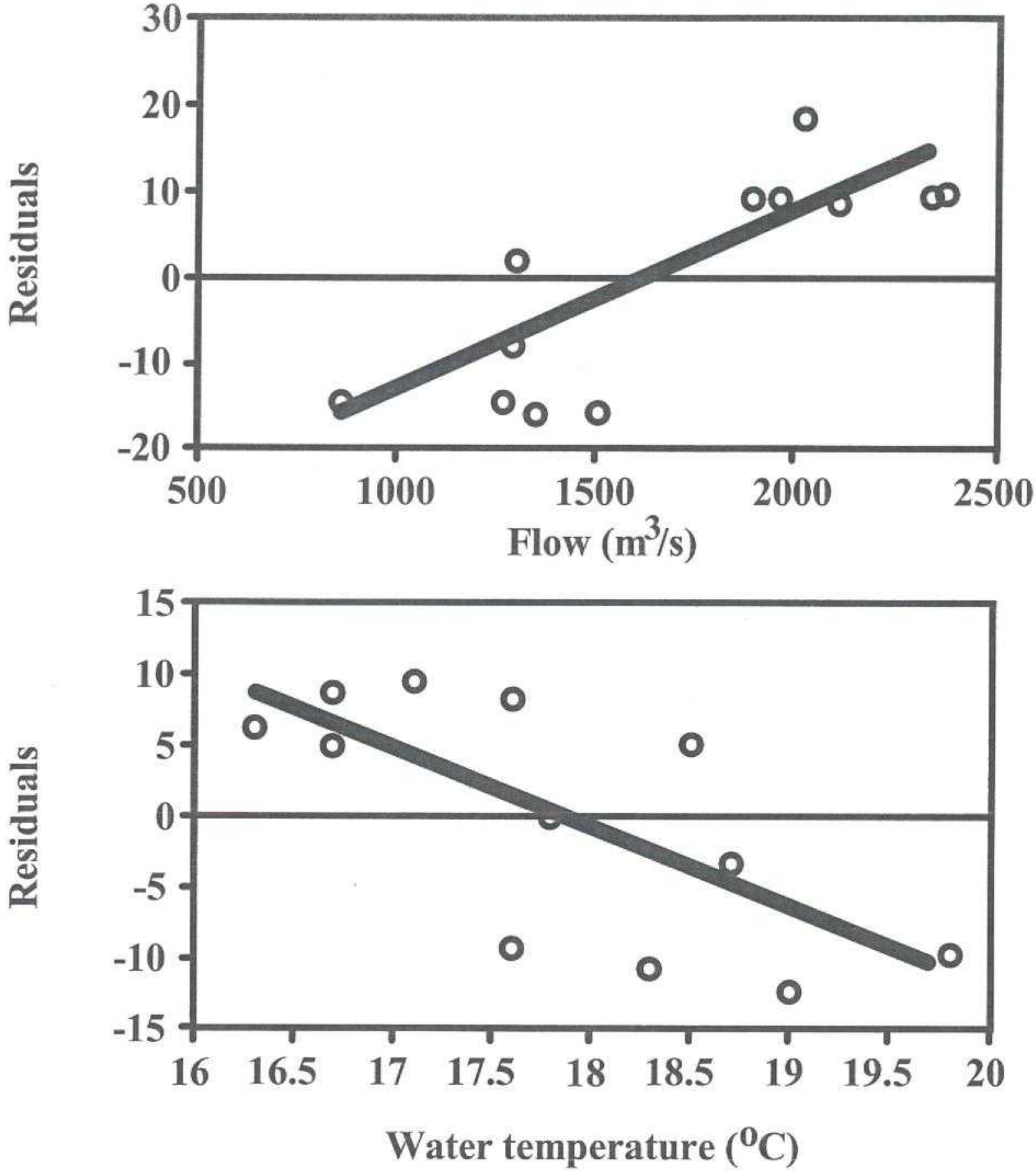


Figure 3.—Residuals plots for flow and temperature. Residuals are from ordinary least-squares multiple regression models fit to predict cohort survival from the predictor variables that is not on the X-axis. The line in each plot was predicted by regressing the residuals against the predictor variable on the X-axis.

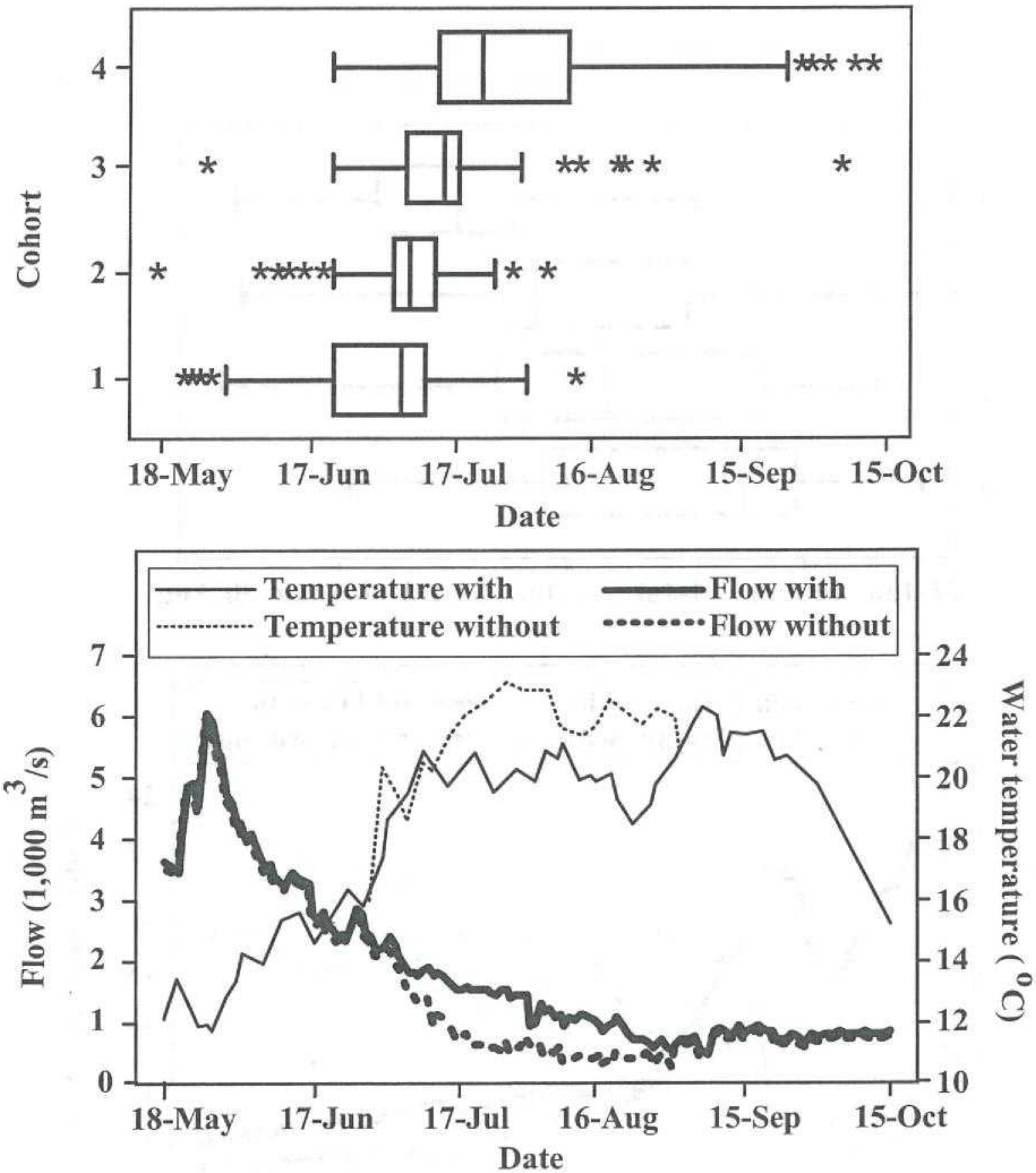


Figure 4.–Box plots showing passage timing at Lower Granite Dam for PIT-tagged wild subyearling fall chinook salmon from each of four cohorts in 1998 (top), and the mean daily flows and water temperatures observed in Lower Granite Reservoir when flow was augmented (with) compared to those that may have occurred if flows had not been augmented (without; bottom). See Figure 2 for a description of box plots.

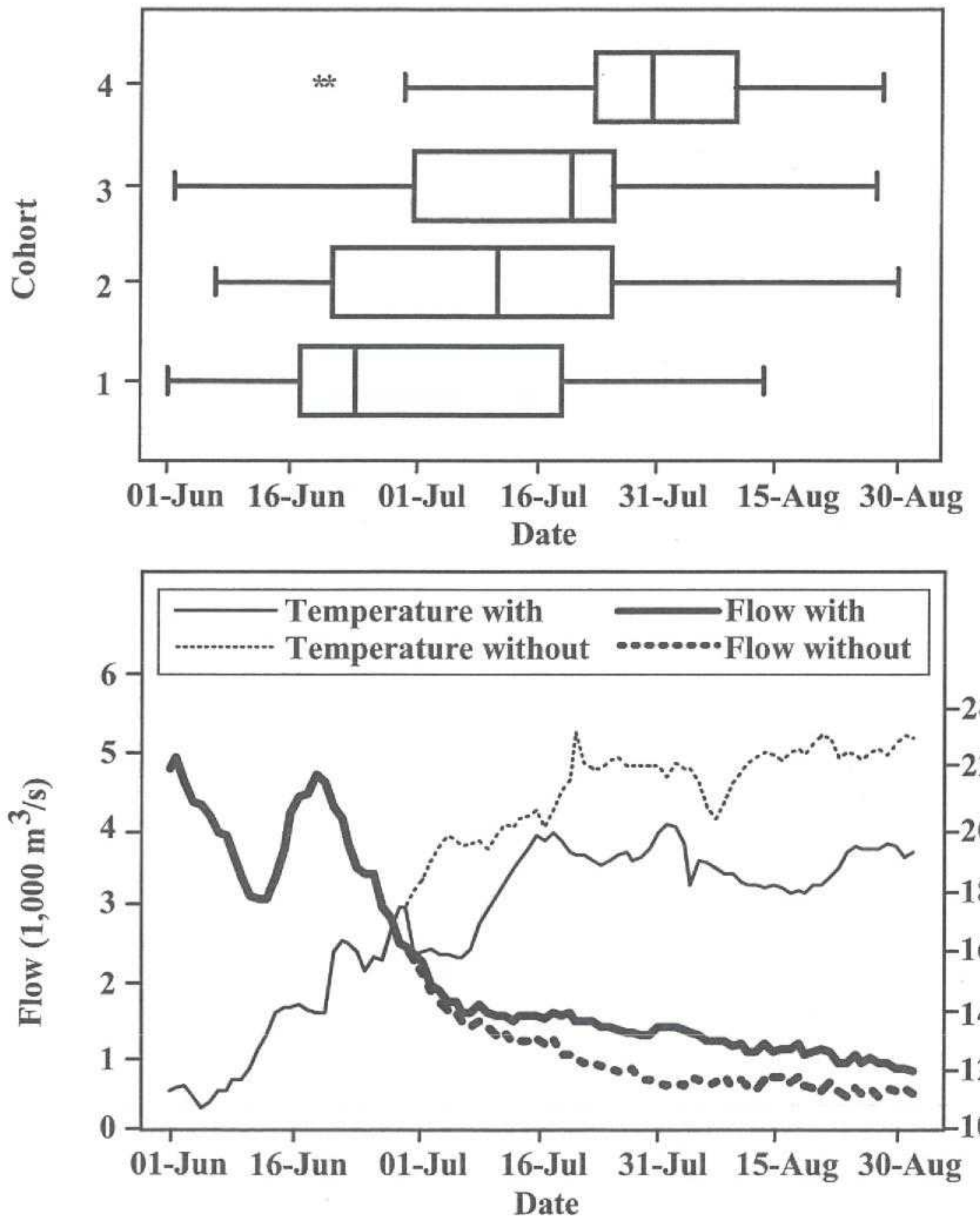
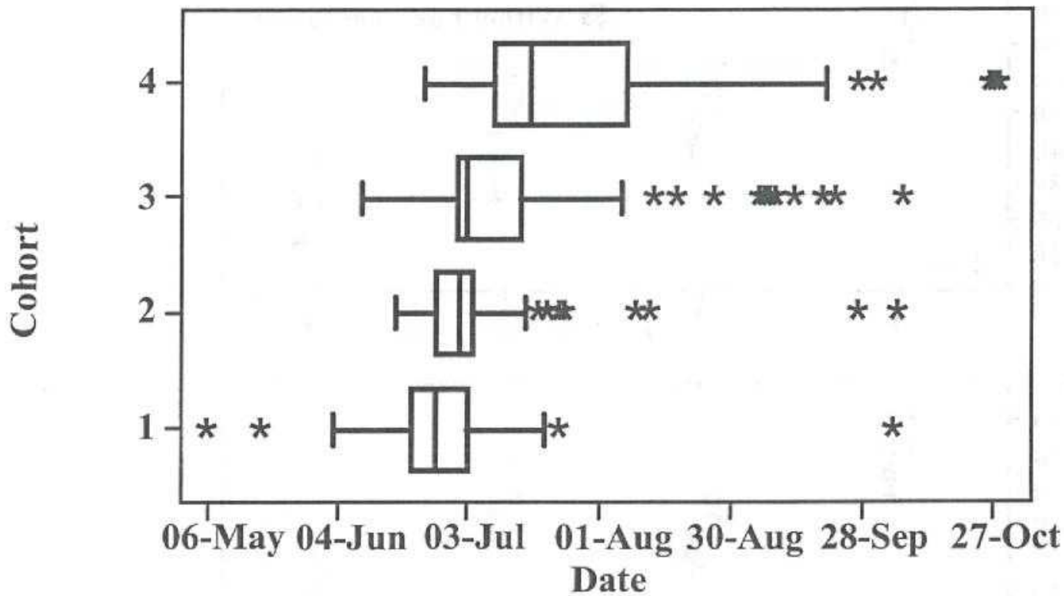


Figure 5.—Box plots showing passage timing at Lower Granite Dam for PIT-tagged wild subyearling fall chinook salmon from each of four cohorts in 1999 (top), and the mean daily flows and water temperatures observed in Lower Granite Reservoir when flow was augmented (with) compared to those that may have occurred if flows had not been augmented (without; bottom). See Figure 2 for a description of box plots.



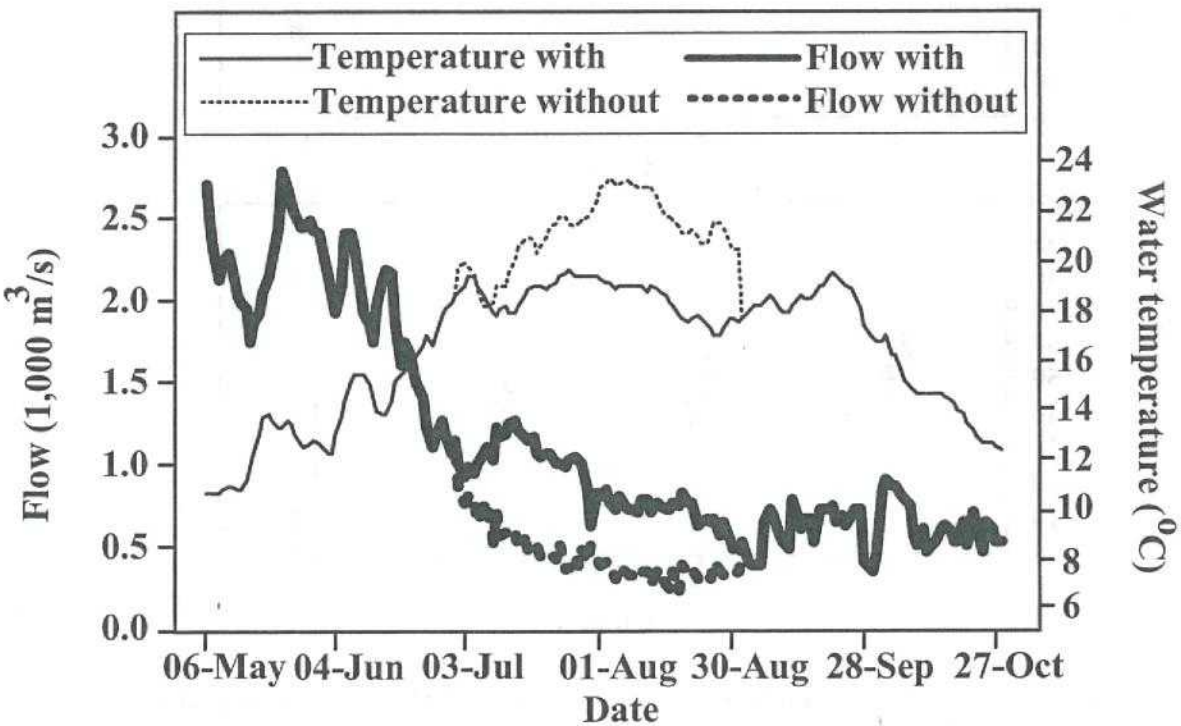


Figure 6.—Box plots showing passage timing at Lower Granite Dam for PIT-tagged wild subyearling fall chinook salmon from each of four cohorts in 2000 (top), and the mean daily flows and water temperatures observed in Lower Granite Reservoir when flow was augmented (with) compared to those that may have occurred if flows had not been augmented (without; bottom). See Figure 2 for a description of box plots.

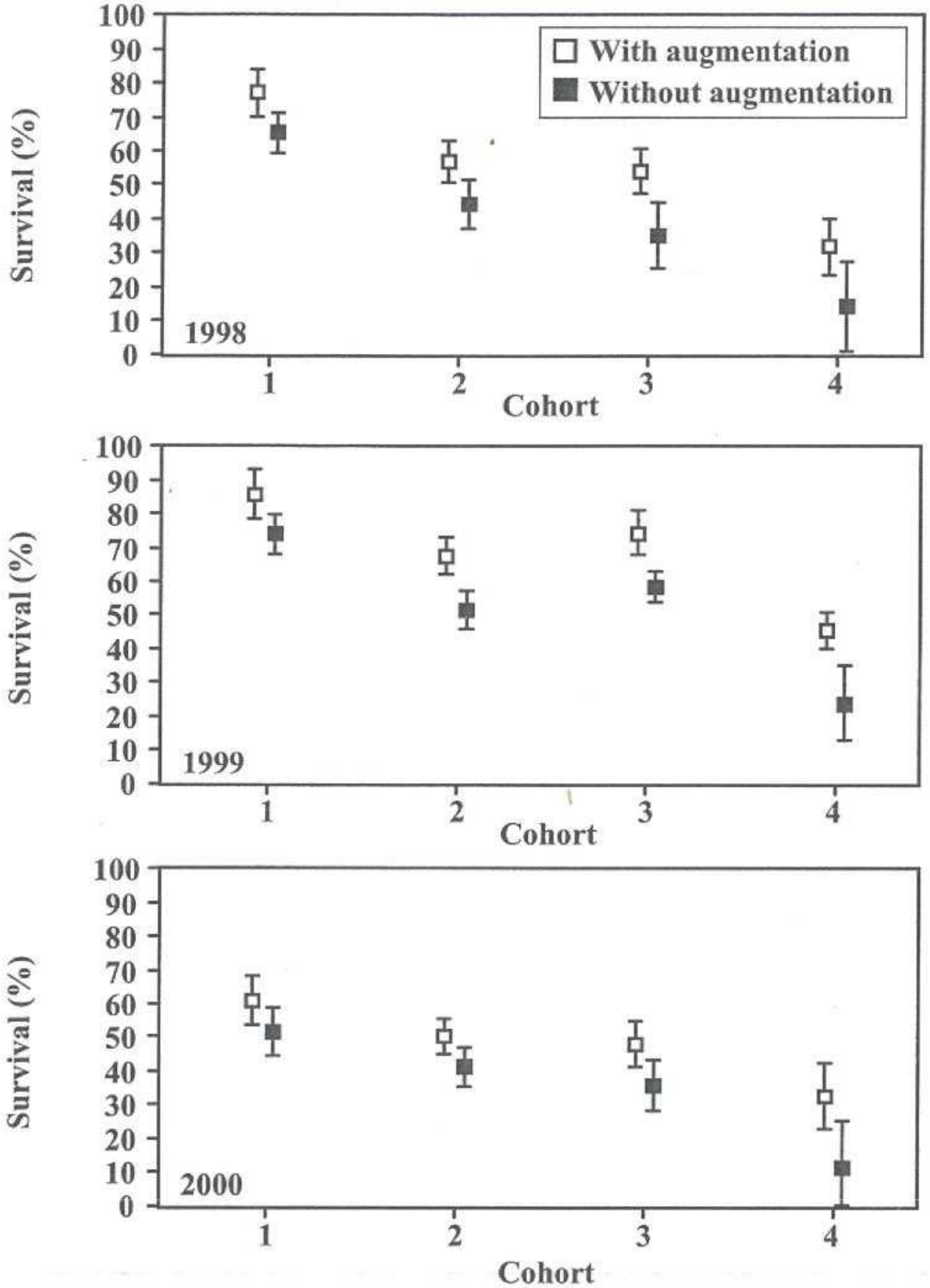


Figure 7.—Survival (±95% C.I.) to the tailrace of Lower Granite Dam for PIT-tagged wild subyearling fall chinook salmon (1998 top; 1999 middle; 2000 bottom) predicted from observed mean flow and water temperatures (from Table 1), and from mean flows and water temperatures recalculated to represent those that would have occurred if flow were not augmented (from Table 3). The equation Cohort survival = 140.82753 + 0.02648 Flow -7.14437 Temperature was used to make both sets of predictions.